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Design of SFR fluidic diode axial port using topology optimization

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ABSTRACT

A fluidic diode is a passive component that direct natural circulation during Loss of Forced Convection (LOFC) in the hybrid-type SFRs. In order to enhance the performance (diodicity) of the existing vortex-type fluidic diode (FD) design, topology optimization, a mathematical method to optimize material distribution in a design domain, is applied to the axial port. In this paper, the topology optimization is conducted for a 2-D axisymmetric domain and two designs with different aspect ratios are finally selected. In this process, design simplification and modification are also conducted based on sensitivity study. Performance of the final optimized designs are validated using detailed 3-D CFD analysis for various parameters, such as Reynolds numbers, entrance lengths, and turbulence models. It is found that the diodicity of the optimized axial port ranges from 1.7 to 2.3 for the low aspect-ratio design (design A) and from 3.7 to 4.5 for the high aspect-ratio design (design B). Friction loss coefficients for the final designs are evaluated for both forward and backward flows using the CFD analysis.

1. Introduction

A Sodium-cooled Fast Reactor (SFR) is a Gen IV reactor concept operating under fast fission neutron spectrum in order to manage high-level minor actinides produced in the conventional nuclear power plants (Fanning, 2007). The use of liquid sodium as a coolant provides efficient heat transfer and avoids the need for neutron moderation as well. There are two SFR designs, loop-type and pool-type, according to the system configuration. The loop-type is a design similar to the conventional light water reactors (LWRs) in which the primary coolant passes through a reactor core, intermediate heat exchangers (IHXs), and primary pumps; which are connected by rigid pipes. In this design, a more compact configuration and easier in-service inspection (ISI) can be achieved, but there is greater probability of sodium leakage and faster transients (Zhang et al., 2008; Zhao et al., 2008). In the pool-type reactor, however, all of the primary components including the reactor core, IHXs, primary pumps, and Direct Reactor Auxiliary Cooling System (DRACS) heat exchangers (DHXs) are immersed in a large pool filled with sodium coolant (Zhang et al., 2008; Zhao et al., 2008). In general, the pool-type design is known to have many advantages including smaller reactor building, milder transients, and low probability of loss of primary coolant accidents. However, the pool-type reactor design requires a larger reactor vessel and complex internal structures with more difficult ISI (IAEA, 1999; ANL, 2006; Niwa et al., 2007).

The hybrid loop-pool reactor is a new SFR configuration proposed by Idaho National Laboratory (INL) in order to improve the economics and safety of the SFRs (Zhao et al., 2008; Neil, 2009). This design achieves the inherent safety of a pool-type design and the compactness of a loop-type design by integration of the concepts of the loop-type and pool-type designs, as can be seen in Fig. 1. The primary system, the hot pool, is a form of a closed loop composed of the reactor core, primary coolant pumps, and IHXs. The primary loop and DHXs are immersed in the cold pool (buffer pool). The hot pool and cold pool are physically separated and thermally coupled by the Pool Reactor Auxiliary Cooling System (PRACS) Heat Exchangers (PHXs). The hybrid-type reactor delivers many advantages such as larger thermal inertia, lower possibility of sodium leakage, system compactness, higher power generation efficiency, and easier in-service inspection with relatively low capital costs. The flow path and the relative flow rate of the primary sodium during normal operation and Loss of Forced Convection (LOFC) transients are depicted in Fig. 1. During normal operation, the heat generated in the core is removed by forced convection of the liquid sodium and then transferred to the intermediate loop through the IHXs. There is a small bypass flow going upward in the PHX resulting in heat loss. Therefore, the upward flow rate should remain extremely low in order to maintain system efficiency. By contrast, during LOFC transients, core cooling is mainly conducted by natural circulation of the liquid sodium, which transfers heat to the cold pool as it passes down in the PHX. In this case, the downward flow rate should be high enough to remove the decay heat in the reactor core (Zhao et al., 2008).

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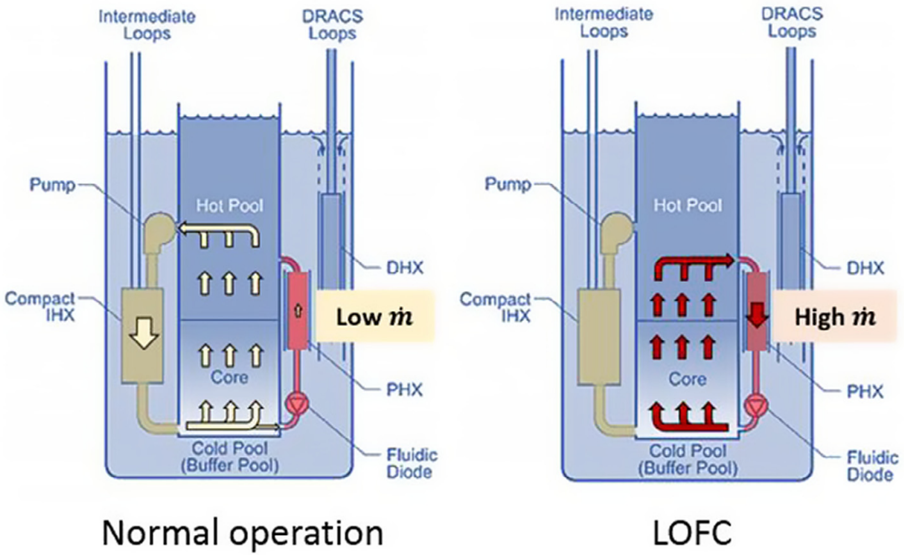

Fig. 1. Flow path and flow rate of primary coolant in hybrid SFR (Zhao et al., 2008).

The fluidic diode (FD) in the PRACS is the key component that passively controls the sodium flow rate and direction, depending on the operating mode. It provides low flow resistance in the forward direction and high flow resistance in the backward direction without any moving parts, which makes it reliable and dependable (Zobel, 1936). Because the resistance of the forward and backward flow is directly connected to the passive safety and plant thermal efficiency, the performance of fluidic diodes has been researched many times and a few candidate designs have been proposed (e.g., ball-type, guide-blade-type, and vortex-type) (ORNL/TM-2009/297, 2009). Among them, a vortex-type fluidic diode is considered to be the most promising because of its long operating history and potential to provide desired flow characteristics (ORNL/TM-2011/425, 2011). The vortex-type fluidic diode generates an irreversible loss of kinetic energy by creating a strong vortex in the backward flow. A schematic of the vortex-type fluidic diode is depicted in Fig. 2. Many efforts have been made to improve performance of vortex-type fluidic diodes by performing parametric studies (ORNL/TM-2011/425, 2011; Kulkarni et al., 2008; Chikazawa et al., 2009). Kulkarni et al. (2008) performed computational fluid dynamics (CFD) analysis with experimental validation to figure out the factors affecting the FD performance, such as chamber geometry, size, aspect ratio, port geometry, and Reynolds number. Chikazawa et al. (2009) performed full-scale experiments using water, for two types of vortex-type fluidic diode and obtained insights into the design modification for better performance. These experiments covering the actual operating condition ($\text{Re} = 6.7 \times 10^4$ for forward flow, $\text{Re} = 1.5 \times 10^5$ for backward flow) on the modified designs showed that both designs meet the criteria of the 50 MW SFR developed by JAEA. A similar study was conducted by ORNL for the Fluoride Salt-Cooled High-Temperature Reactor (FHR) (ORNL/TM-2011/425, 2011). Parametric study on several candidate designs was performed with FLUENT code to determine the dimensional parameters needed to meet the operating criteria (e.g, chamber diameter and inlet diameter). The performance of the selected design was validated by experiments using water as a working fluid.

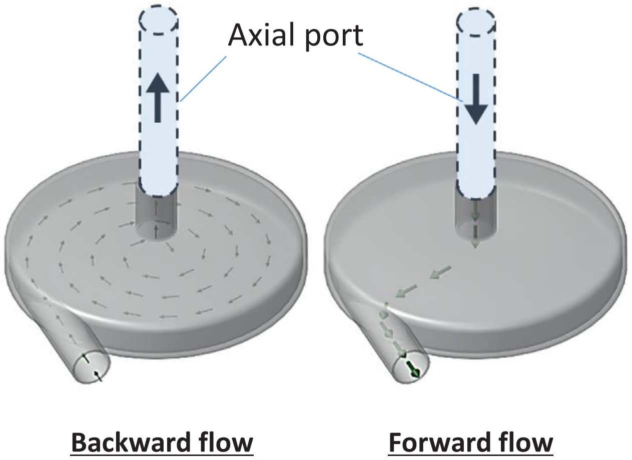

Fig. 2. Schematic of flow passing the vortex-type fluidic diode (ORNL, 2011).

This study applied a topology optimization (TO) to improve the existing vortex-type fluidic diode design and evaluated its performance through computational fluid dynamics (CFD). The topology optimization was applied to the axial port between the FD and the PHX, as depicted in Fig. 2. Topology optimization is a mathematical method to optimize the material distribution in the design domain with predefined boundary conditions. It has been originally developed for structural design (Bendsoe and Kikuch, 1988) and the application has been extended to fluid flow by Borrvall and Petersson (Borrvall and Petersson, 2003). Many studies have been conducted recently in the areas of flow applications including 2-D Stokes flow (Gersborg-Hansen et al., 2006), microfluidics (Olesen et al., 2006; Andreasen et al., 2009), 3-D Stokes flow (Aage et al., 2008), and 2-D catalytic microfluidic reactor design (Okkels and Bruus, 2007). For industrial applications, the possibility of topology optimization for the air ducts in the car was demonstrated by Volkswagen engineers (Othmer et al., 2006).

2. Topology optimization of fluid flow

2.1. Governing equations: Hydraulic model

Topology optimization is a mathematical method to optimize material distribution in a design domain where a boundary condition is applied. It has been implemented using the finite element method (FEM) and numerical optimization methods such as methode of moving asymptotes (MMA), genetic algorithms (GA), and sequential quadratic programming (SQP) (Zheng et al., 2013).

The fundamental concepts of the fluid flow topology optimization consist of an objective function ($\Phi(\gamma, s(\gamma))$, the variable to be minimized), a design variable (γ, the variables defining the geometry), flow variables ($s(\gamma)$, the flow-related variable that depends on the geometry), and constraints ($R(\gamma, s(\gamma))$, the conditions that should be